The pathophysiology of IAHS,\textsuperscript{11} or idiopathic normal-pressure hydrocephalus,\textsuperscript{1} is still an enigma. Today two principally different mechanisms are considered: 1) an altered hydrodynamics of the CSF system; and 2) a parenchymal, possibly ischemic, process. The former is demonstrated by modestly raised ICP, increased CSF Rout,\textsuperscript{31} and the presence of abnormal B-wave patterns;\textsuperscript{13} the latter is indicated by cortical and subcortical decreased blood flow\textsuperscript{27} and metabolism\textsuperscript{2,42} as well as periventricular white matter lesions.\textsuperscript{26} In addition, increased blood pressure is a risk factor.\textsuperscript{25}

The only viable treatment today is shunt surgery;\textsuperscript{43} however, only 70% of patients who receive shunts improve clinically,\textsuperscript{32} which probably is due to difficulties in selecting appropriate patients. The selection of suitable patients for shunt surgery is based on a variety of examinations\textsuperscript{43} and one involves assessing the functionality of the CSF system. Evaluating the functionality of this system involves measurements of specific hydrodynamic parameters such as ICP, Rout, and elastance but also targets a less specific characteristic, namely the presence of B-waves.

Several CSF hydrodynamic tests are used to assess Rout. The basic concept is to study the pressure-infusion curve through either constant flow infusion\textsuperscript{22} or constant pressure infusion.\textsuperscript{18} Elastance is determined by using bolus injections to measure the PVI of the CSF pressure–volume curve,\textsuperscript{33} where PVI is the volume needed to increase the pressure 10-fold.

Other methods measure how ICP is influenced by the combined effect of elastance and volume change. Examples include the CSF pulse pressure method\textsuperscript{3} and the ICP waveform analysis,\textsuperscript{16} which both make use of the pulsatory changes in the intracranial blood volume and their transformation into pressure waves in the CSF system.

The B-waves are slow and rhythmic oscillations in ICP.\textsuperscript{29} They probably originate from oscillations in cerebral blood volume\textsuperscript{16} and may be present in healthy individuals as well.\textsuperscript{35} Examination of B waves is invasive, involving surgical insertion of a probe followed by pressure registration lasting for several hours. In general, the results of the registration are evaluated visually by clinicians, but recently we have described a computerized method of calculating the B-wave presence of an ICP recording.\textsuperscript{17}

The various methods used to measure the hydrodynamic properties of the CSF system have not been properly compared. Consequently, the internal relations between the aforementioned parameters are unknown. If the presence of B-waves could be explained by other parameters, it would...
be possible to replace overnight ICP recording and B-wave analysis with simpler methods to select patients likely to benefit from shunt placement.

In this study, we compared three methods based on an extended model of the CSF system (Fig. 1 upper). Our aim was to ascertain how the B-wave pattern in patients with IAHS is related to Rout, which was measured using the constant pressure infusion method, and to the newly defined parameter of RPPC, which was derived from the CSF pulse pressure method.

**Clinical Material and Methods**

**Patient Population**

The population in the current prospective study was part of a larger series of patients with IAHS. This larger series included two main CSF hydrodynamic studies: an overnight ICP registration and a constant pressure infusion test. Microdialysis and monitoring of brain tissue PO2 were also performed. The local ethics committee approved all aspects of both the larger series and the smaller study and informed consent was obtained from all patients.

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Fig. 1. *Upper: Schematic of current–circuit model, once described by Marmarou, illustrating the hydrodynamics of the CSF system. Currents in the model symbolize flows in the CSF system. When ICP exceeds dural venous pressure (Pd), the switch closes and a CSF absorption flow (IA) occurs through a non–pressure-dependent resistor representing Rout. The CSF storage flow (IS)—that is, the CSF volume rate of change—is associated with the elastance of the CSF system, and the storage capability is represented by a pressure-dependent capacitor. The production of CSF generates a one-way production flow (IP). Similarly, the ability to withdraw or add CSF/mock CSF produces a two-way infusion flow (II). To consider volume oscillations of the intracranial blood compartment, the model is extended by an alternating current (IB) that represents the blood volume change rate. These oscillations, including pulse waves and B waves, are transferred to the CSF system and affect the distribution of CSF. Lower: Graph illustrating that the relative distribution between storage flow (solid line) and absorption flow (dashed line) in the CSF system depends on the wavelength (T) of the imposed volume oscillation. Shorter waves, such as pulse waves (T = 1 second \( \rightarrow \log T = 0 \)) and B-waves (T range of 30–120 seconds \( \rightarrow \log T \) range of 1.5–2.1), lie in the storage zone; that is, almost 100% of these volume oscillations are dealt with by reallocation and storage of CSF, whereas longer waves of 30 minutes (T = 1800 seconds \( \rightarrow \log T = 3.3 \)) are needed to create an evenly distributed flow. Infinite wavelength, which is the approximate situation during a constant infusion test, yields a 100% absorption flow, and the test can therefore be used to determine Rout. The curves for the flows are calculated using the circuit analysis of the model in Fig. 1 upper. See the Appendix for details.*
consent was obtained from each patient prior to the hydrodynamic examinations.

This study was based on 10 patients—eight men and two women—with typical radiological signs of IAHS, that is, communicating hydrocephalus with no signs of major ischemic lesions, severe cortical atrophy, or widespread white matter lesions. Clinically, all patients showed the characteristic gait disturbance (a compulsory sign that was recorded by video) often accompanied with mental decline and/or incontinence. The mean patient age was 72.4 years (range 55–78 years) and the mean duration of gait disturbance was 28 months (range 12–60 months).

After finishing all examinations, all patients were offered a shunt based on the comprehensive picture of their clinical, radiological, and hydrodynamic data. All patients agreed to undergo shunt placement and 1 to 2 months after the examinations each of them received a CSF shunt device. At the 3- to 6-month follow up after shunt surgery, nine of 10 patients (Cases 2–10) experienced gait improvement.

Assessment of B Waves

The steps involved in overnight ICP registration and B-wave analysis have previously been described.31 In brief, an intraparenchymal ICP transducer (Codman microsensor; Johnson & Johnson Professional, Inc., Raynham, MA) was inserted in the morning. The ICP registration started at approximately noon on the same day and was finished at 8 a.m. the following morning (range 17.5–20.8 hours). The patient was lying in bed, awake or asleep, during the entire period of data collection. The sampling rate was 100 Hz and data were recorded on a PC (Power PC 7600; Apple Computer, Inc., Cupertino, CA) by using a multimodal recording system including a data acquisition card (MIO16X50; National Instruments, Inc., Austin, TX) and commercially available software (LabVIEW; National Instruments). The 100-Hz data were averaged over 1 second, giving an actual sampling rate of 1 Hz, and were analyzed using a program developed in LabVIEW and solely designed for the purpose of B-wave analysis.

The program filtered the ICP data through a digital bandpass filter of the Butterworth type (5th order), which cut off frequencies outside the B-wave interval of 0.5 to 2 minutes. The B waves were revealed using a computer algorithm for individual wave analysis. A wave was classified as a

B wave if the absolute value of its peak or trough equaled a minimal threshold value of 1 mm Hg. A wave was defined as a new wave when the data passed the zero level. The B% was calculated as the accumulated time with intervals classified as B waves divided by the total time.

Determination of CSF Rout

Determination of Rout was made using the previously described method of constant pressure infusion.30 In short, at 8 a.m. on the second day, directly after the B-wave examination, two needles were inserted into the lumbar subarachnoid space while the patient was sitting upright. Free passage was assessed and the patient was then placed supine. Drainage and infusion of real or artificial CSF were performed using a peristaltic pump (MS-1 REGLO=160; Ismatec SA, Zurich, Switzerland) through one of the lumbar needles. Using the other lumbar needle, data acquisition and pressure regulation were performed with the aid of an electronic control unit developed at Umeå University and LabVIEW software run on a PC with a data acquisition board (MacADIOS; GW Instruments, Inc., Somerville, MA). Pressure measurements were conducted using an ICP monitoring kit (Becton, Dickinson, and Company, Franklin Lakes, NJ) calibrated at 0 and 22.5 mm Hg. The zero pressure level was calibrated in the cranial sagittal center, which was defined as the midpoint between the highest and lowest point of the body placed supine.

Outflow resistance was determined by applying three pressure levels (two in patients in Cases 1–3) above resting pressure to the CSF space (Fig. 2), while recording the required rate of artificial CSF inflow. The first applied pressure was at least 7.5 mm Hg above resting pressure, where-
Cerebrospinal fluid pulse pressure and B waves

As the last and highest level was always 41.5 to 45 mm Hg. When an intermediate pressure level was used, it was applied halfway between the first and last (highest) level. The lower levels were shorter in time (10–15 minutes), whereas the top level lasted for 20 to 30 minutes. The last level was terminated by halting the pump, and ICP returned to its resting pressure. Finally, the CSF system was drained before the test was finished. Corresponding flow/pressure values were plotted, and the slope, which was equal to the inverse of R_out, was determined using linear regression.

Assessing RPPC by the CSF Pulse Pressure Method

The basic principle of the CSF pulse pressure method is to measure the pulsatory ICP amplitudes at different ICPs. The application of the method and its necessary definitions are explained in Fig. 3. The derivation of the RPPC is also described.

To detect ICP amplitudes during constant pressure infusion, pressure data from the ICP monitoring kit were continuously sampled from the lumbar subarachnoid space at a frequency of 100 Hz. Data were conveyed to a PC by an experimental setup that was identical to the one used in the B-wave examination. The ICP amplitude can be adequately determined during the relaxation phase of the constant pressure infusion (Fig. 2) because the pump is at rest and cannot interfere with the natural shape of the amplitude. In addition, ICP passes through a vast pressure interval while relaxing toward its resting pressure. The relaxation phase is divided into 2-second intervals, which ensured that one heartbeat was captured within each interval. Pressure data from each interval were then analyzed using a computer algorithm developed in LabVIEW. The computer algorithm was designed to single out the maximal and minimal pressures in each interval, yielding a total of 300 pairs of maximal/minimal values. Pressure trends were ignored. We defined the RPPC to describe quantitatively the change in pressures in each interval, yielding a total of 300 pairs of data from each interval. The RPPC was determined using linear regression. The B-wave percentage, Rout, and RPPC were compared using linear regression:

\[ \text{B\%} = c_1 \times \text{RPPC} + m_1, \]

(1a)

\[ \text{B\%} = c_2 \times \text{R_out} + m_2, \]

(1b)

\[ \text{RPPC} = c_4 \times \text{R_out} + m_4, \]

(1c)

where \( c_i \) is the regression coefficient and \( m_i \) is the interception of the regression line with the dependent variable axis.

The B-wave percentage, Rout, and RPPC were compared using linear regression:

\[ \text{B\%} = c_1 \times \text{RPPC} + c_2 \times \text{R_out} + m_5, \]

(2)

Second, Rout was added to Equation 1a as an explanatory variable and a forward multiple regression was performed:

\[ \text{B\%} = c_1 \times \text{RPPC} + c_2 \times \text{R_out} + m_6. \]

(3)

The coefficient of correlation and probability value were determined for the regression coefficients and the level of significance was set at 0.05.

Results

The results from the B-wave analysis (B%), constant pressure infusion (R_out), and RPPC are presented in Table 1. The relationship between B% and RPPC shows a significant correlation (\( r = 0.91, p < 0.001, 10 \) patients), whereas no significant correlation was found between either B% and R_out (\( r = 0.59, p = 0.07, 10 \) patients) or R_out and RPPC (\( r = 0.55, p = 0.10, 10 \) patients). The residual analysis did not show a correlation (\( r = 0.22, p = 0.54, 10 \) patients); hence, resistance cannot account for what is left to explain after using the linear B%–RPPC model. A forward multiple regression demonstrated that adding R_out as an explanatory variable does not yield a significantly better correlation compared with the linear B%–RPPC regression.

Discussion

Despite the B waves’ unknown relation to other param-
eters of the CSF system, their presence in ICP recordings has been used to select patients with IAHS for shunt surgery ever since Lundberg defined them. Our data demonstrate a strong correlation between the presence of B-waves and our defined RPPC, indicating the possibility of replacing the former with the latter to select shunt-responsive patients with IAHS.

**The RPPC, Elastance, and B Waves**

The linear regression between \( \Delta P \) and \( P_{\text{mean}} \) (Fig. 4), defining the RPPC, showed a high correlation in each individual case (Table 1). Similar analyses performed in animals and humans demonstrate high correlations, well, despite differences in methodology. This result indicates a robust method.

The RPPC and elastance are not the same, which would explain why previous attempts to correlate B-waves with elastance have failed. Elastance determines the pressure–volume curve, whereas RPPC is determined by the combined effect of elastance and volume change, the latter of which results from intracranial blood pulsations. Thus, RPPC can be interpreted as an individually scaled parameter that reflects the total strain put on the CSF system by pulsating blood flow.

Previous work has revealed weak correlations between elastance and RPPC, which probably is due to the variability in intracranial pulsation volume among individuals. Cases of stronger correlations have been reported, but any comparison would be tenuous because the RPPC was defined differently.

**The RPPC, \( R_{\text{out}} \), and B Waves**

Our results indicate a correlation between RPPC and \( R_{\text{out}} \) but not a significant one; a similar relationship was found between B waves and \( R_{\text{out}} \). In contrast, the correlation between B% and RPPC was highly significant. This piece of evidence along with the results from the residual analysis and the multiple regression thoroughly supports the assertion that RPPC alone is the parameter that most accurately indicates the B-wave presence.

In the literature, both weaker and stronger correlations between B waves and \( R_{\text{out}} \) have been reported. Additionally, B waves have been found to correlate exponentially with the sum of \( R_{\text{out}} \) and the inverse of elastance. Any differences may depend on methodological issues, such as variability in methods of measuring \( R_{\text{out}} \) and subjectivity in the definition and visual interpretation of B waves. Nonhomogeneous groups of patients, arising from erroneous or indefinite IAHS diagnosis may contribute to the inconsistencies as well. Results of our residual analysis and multiple regression demonstrate that the correlation between B waves and \( R_{\text{out}} \) could be secondary to the correlation between \( R_{\text{out}} \) and RPPC.

**The B Waves and RPPC: an Explanatory Model**

The close link between B waves and RPPC can be explained by taking into consideration an extended model of the CSF system (Fig. 1). Pulse waves—most likely B waves—originate from intracranial blood volume oscillations (I in Fig. 1). These oscillations are then transferred to the CSF system, in agreement with the Mon-roe–Kellie doctrine. The CSF system can deal with imposed oscillations in two separate ways: either reallocate them within the system, thereby imitating CSF storage (storage flow, \( I_s \)), or divert them out of the system by absorbing CSF (absorption flow, \( I_a \)). Thus, the distribution between the two—that is, how much is stored and how much is absorbed—depends on the wavelength of the blood oscillation, ICP, PVI (that is, elastance), and \( R_{\text{out}} \).

By using common numbers in the context of IAHS, it can be shown that the CSF system primarily uses storage, not absorption, to deal with both pulse waves and B waves. Thus, despite a much longer wavelength, B waves reflect the same functional portion of the CSF system as the RPPC, namely its ability to temporarily reallocate and store supplementary intracranial volumes.

**Idiopathic Adult Hydrocephalus Syndrome, B Waves, and Shunt Surgery**

Researchers at centers with a long practice in IAHS maintain that approximately 70% of patients improve after shunt surgery. From this perspective, the 90% improvement rate in our study reflects a correct initial diagnosis in our patients.

In the hands of some, the usefulness of B-wave analysis to predict response from shunt surgery is substantiated. Others assert that more solid scientific evidence is needed before we can speak knowingly of the precision of B waves in corroborating IAHS and predicting shunt responsiveness. Today, there is no conclusive proof that either B-wave examination or other methods, such as \( R_{\text{out}} \) measurements, magnetic resonance imaging, or tap tests, can accurately forecast the benefit of a shunt in a general case of IAHS. The methods are likely to be complementary. Hence, there is a great need to develop a more reliable test to select patients with IAHS for shunt surgery, especially in cases in which the diagnosis is indefinite. In agreement with the described pattern of inconclusiveness, this study revealed no distinct deviation in B-wave presence or \( R_{\text{out}} \) in a comparison between the nine patients whose condition improved and the one patient whose condition did not.

Regarding accessibility to the method, note that B-wave analysis is limited to centers where ICP monitoring can be performed, thus demanding facilities that offer both neuropsychological procedures and pressure registration. Measuring \( R_{\text{out}} \) or using the CSF pulse pressure method is less complex, requiring lumbar pressure regulation only, and magnetic resonance imaging and spinal tap tests are widely available methods.

**Conclusions**

Our data demonstrate a strong correlation between RPPC and the presence of B waves. This result indicates that B waves—like RPPC—primarily reflect the functionality of reallocation and storage rather than absorption in the CSF system.

The CSF pulse pressure method has obvious advantages. By adopting the same lumbar infusion technique that determines \( R_{\text{out}} \), one can assess the same hydrodynamics in 10 minutes as those revealed in a B-wave examination lasting several hours. Furthermore, the method is not limited to use...
Cerebrospinal fluid pulse pressure and B waves

in patients with IAHS and may be useful in other cases of intracranial monitoring as well.

Using an objective B-wave analysis and a homogeneous patient population enhanced the reliability of our results, and we conclusively believe that the RPPC measured with the CSF pulse pressure method may replace the B-wave analysis as a means of selecting patients with IAHS who will benefit from shunt placement.

Appendix

By applying circuit analysis to the model in Fig. 1 upper, the ratio between CSF storage and absorption flow is calculated as follows:

\[
\frac{I_s}{I_a} = \frac{2 (\pi \times f \times C)/(1/R_c)}{\frac{1}{k} - \frac{1}{2.5} \times \frac{P}{\text{ICP}}},
\]

where \( f \) is the wave frequency and \( C \) is the compliance, that is, the inverse of elastance. If \( C = 1/(k \times P) \), then

\[
\frac{I_s}{I_a} = \frac{\text{Rout} \times \text{PVI} \times 2 \pi \times 0.4343 / \text{ICP}}{\text{T} / 2600},
\]

where \( T \) is the wavelength. More specifically, if values of \( \text{Rout} = 15.1 \text{ mm Hg} \times \text{min/ml}, \text{ICP} = 16.6 \text{ mm Hg} \), and the PVI of hydrocephalus material = 17.5 ml, then

\[
\frac{I_s}{I_a} = 2600/T,
\]

where \( T \) is measured in seconds. To determine what proportion of blood volume oscillation (\( I_s \)) is distributed as storage flow (\( I_s \)) and absorption flow (\( I_a \)), the two latter are divided by the former, yielding

\[
\frac{I_s}{I_s + I_a} = \frac{2600(2600 + T)}{2600 + T} \quad (5a)
\]

for the storage flow and

\[
\frac{I_s}{I_s + I_a} = \frac{T}{2600 + T} \quad (5b)
\]

for the absorptive flow.

Plotting Equation 5a and b against the logarithm of \( T \) generates the graph featured in Fig. 1 lower.

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